

Extinguishment of Combustible Porous Solids by Water Droplets

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1990, Fire Growth and Extinction

ABSTRACT

This report presents a brief summary of previous research on fire suppression with the objective to provide guidance for the present work. Reasons for the adopted methodology are summarized and the apparatus developed for the study is described. Finally, some results for PMMA are presented along with conclusions and future work.

Two experimental configurations are chosen for this study: (i) *Stagnation-point flow apparatus*: which allows studying both the *gas-phase* and the *condensed-phase* suppression actions and enables transient chemical measurements in the exhaust gas. These measurements are used to study the suppression mechanisms and quantify the suppression effectiveness. (ii) *Counterflow diffusion flame apparatus*: which allows detailed flame structure measurements but is limited to studying *gas-phase* suppression mechanisms (chemical and/or physical). Initially, the work is done using the stagnation-point flow apparatus with water as the extinguishing agent and PMMA as the burning solid to establish a standard for comparison of suppression effectiveness of various agents.

Our experimental results for PMMA show that there are two simultaneous effects as a result of water application: (i) chemical enhancement of the burning rate (which is important only when the flames are sooty; Note: most fires are sooty), and (ii) physical cooling of the solid via water evaporation. The chemical effect has not been previously noted because water is usually applied in much greater quantities than needed and in this domain the physical cooling effect dominates. Thus, future work is directed toward better understanding the suppression mechanisms.

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for

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1. INTRODUCTION

Fast and efficient suppression of accidental fires is of great importance for fire safety. Yet, research on fire suppression is severely lacking. This is probably because fire suppression adds another dimension of complexity to the already complex fire problem. Suppression can be usefully defined as reduction in severity of an unwanted fire caused by external actions aimed at extinguishment. To scientifically improve the effectiveness of these suppression actions, it is essential to quantify the terms "reduction in severity" and "time to extinguishment" such that they can be experimentally measured and mathematically evaluated. Since all fires eventually self-extinguish when they run out of fuel, we need to quantify these terms as a function of the suppression action. Clearly, to save lives and property, the goal of suppression research must be to minimize the *time to extinguishment* or maximize the *suppression rate*¹.

The above criterion immediately poses the question -- "minimize and/or maximize with respect to what?" If the quantity of the suppression agent (measured in moles, gms, volume, etc.) is taken as the independent variable for the minimization process, then one may define a "*suppression effectiveness*" of the agent as the suppression rate per unit mass of the agent applied¹. However, in trying to evaluate an agent's suppression effectiveness according to this definition we encounter additional difficulties. For example, the suppression effectiveness is clearly zero, for any agent, if the agent does not reach the fire location. Thus, the effect of the application method² on the agent's effectiveness must also be quantified. Only when the most effective application strategies for various suppression agents have been determined, will it be possible to evaluate and compare their suppression effectiveness.

Thus, as a first step toward improving suppression technology, we need to develop an experimental and theoretical framework that will provide a quantitative understanding of the mechanisms (chemical and/or physical) responsible for extinguishment and enable the determination of:

- (1) Suppression rate, (2) Time to extinguishment, & (3) Application strategy.

This work seeks to address this research problem through well-controlled small-scale laminar stagnation-point flow and counterflow diffusion flame experiments and modeling. An obvious

¹The terms *suppression rate* and *suppression effectiveness* are not precisely defined in the literature. In the present context we may think of suppression rate as KW reduction in the fire's heat release rate as a result of suppression action and suppression effectiveness as KW reduction in the heat release rate of the fire/gm of the suppression agent applied. Suppression effectiveness may be normalized with the heat release rate per unit mass of the fuel to result in a non-dimensional quantity of order unity.

²Application method or application strategy may be thought of as a prescription for the agent's distribution in space and time. Mathematically, the agent's mass flux $\dot{m}''(\vec{r}, t)$ gm/cm² sec may be used to describe this distribution.

question is: will it be possible to scale the results of these experiments having a characteristic dimension of a few centimeters, to room fires that may be a few meters across or oil spill fires that may be 100 meters across? Clearly, there are changes in mechanisms governing transport of heat and mass with changes in scale: most notably turbulence and radiation. While it is not possible to directly scale the results of the proposed small-scale laminar experiments, these experiments are designed to represent the local behavior of large turbulent diffusion flames. Later, with the assistance of appropriate mathematical models such as those being developed by Dr. Howard Baum of NIST, large-scale predictions will be possible. This is the primary reason for choosing the counterflow diffusion flame configuration. Counterflow diffusion flames are also ideal because they provide a one-dimensional field convenient for both experimental measurements and theoretical modeling. They permit an integrated experimental & theoretical program that is urgently needed to develop a basic understanding of the suppression mechanisms.

To summarize, the objective of this continuing work is to develop a fundamental experimental and theoretical framework to: (i) provide a quantitative understanding of the chemical and physical mechanisms responsible for extinguishment (obtained via. small-scale experiments and models), (ii) enable determination of the suppression rate, time to extinguishment and agent application strategies, (iii) enable evaluation of the suppression effectiveness (needed for rational comparison of various suppression agents).

2. BACKGROUND

Literature on fire suppression falls into two broad categories; one which is concerned with the physical suppression mechanisms (such as cooling, dilution and reactant removal by mechanical or other means; Ref. 1-44) and the other which is concerned with chemical inhibition (Ref 45-73). In conjunction with the above discussion, attention is primarily focused on understanding the suppression mechanisms.

Suppression by Physical Means:

Physical suppression actions may be broadly classified into:

- (i) Suppression agent or action directed at quenching the gas-phase combustion reactions. This may be accomplished by simply blowing-off the flame (i.e. by increasing the strain rate) or by diluting the fuel and/or the oxidizer streams by inerts such as H_2O , CO_2 , and N_2 or by cooling the reaction zone. Physical mechanisms responsible for cooling are the agent's heat capacity, heat of vaporization or sublimation (if the agent is a liquid or a solid) and the heat of thermal decomposition (if the agent decomposes prior to acting). The presence of the agent may also enhance radiative heat losses from the combustion zone.
- (ii) Suppression agent directed at cooling the condensed-phase to inhibit fuel pyrolysis (e.g. water application). This method is energetically advantageous since only a small part of the heat feedback fraction of the chemically released energy must be removed. Heat feedback is approximately 10% of the chemical enthalpy and roughly

a third of this needs to be removed to extinguish the flames. Some agents also block the radiative heat feedback to the burning liquid or solid.

- (iii) Separating the reactants by mechanical or other means such as by blanketing. An excellent example of this suppression method is the use of aqueous foams to extinguish liquid hydrocarbon fires.

Clearly, combined extinguishment actions are also possible and in-fact desirable. These may occur naturally, as in the case of water application, where the pyrolyzed fuel is also diluted by evaporated water vapor.

Physical suppressants such as H_2O , CO_2 , N_2 , are thought to be chemically inert in a fire. They are widely used to suppress fires because of their easy availability, low cost and nontoxic and noncorrosive properties. Among these, water is the most common suppression agent and probably the only possible agent for large fires. In addition to being outstandingly nontoxic, it also has the highest heat of vaporization among non-flammable liquids providing an excellent heat sink. Yet, water is not ideal for all conditions. It freezes at $0^\circ C$, conducts electricity, causes irreversible damage to some items and is not compatible with certain metals and chemicals.

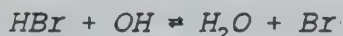
Suppression by Chemical Inhibitors:

Known chemical suppressants are either halons or dry chemical powders. In addition to their physical action of cooling and dilution, they are believed to interfere with the critical reaction steps responsible for maintaining the flame. There is a substantial body of literature on chemical suppressants and their evaluation methods. Most of these investigations utilize premixed flames and provide information regarding the effects of suppressants on flame propagation velocity and flammability limits [see Ref. 27, 45-54]. Some studies regarding the effect of halons on diffusion flames have also been conducted [see Ref. 55-60]. Several excellent reviews are also available in the literature [4-6, 18, 21, 25, 46, 47, 61, 62].

Halons are usually gases at room temperature and pressure and are used to flood an area. Their distinctive feature is that currently there are no known other inerting agents that permit a space to be flooded while retaining breathability. Thus, they are often used in situations where personnel must remain during fire emergencies or where water or dry chemicals will cause irreversible damage. Halon 1301 (CF_3Br) is by far the most popular because of its low toxicity and comparatively high effectiveness.

Since halons usually reach the combustion zone as a gas via compartment flooding operations, condensed-phase cooling does not occur leaving it susceptible to re-ignition. Halon action is thus limited to the gas-phase combustion process. Experiments have shown that only about 5% halon 1301 in air is sufficient to prevent propagation of a premixed flame in any methane/air mixture. By

contrast, about 25% CO_2 is required to obtain the same result³. This strongly points to the chemical action of Halon 1301. It is believed that CF_3Br decomposes in the flame to produce HBr , and HBr then acts to remove H atoms and OH radicals, by the following reaction mechanism:



This effectively slows the chain branching reaction responsible for sustained flaming ($H + O_2 \rightleftharpoons O + OH$) by reducing the H atom concentration. In addition to destruction of chain carriers, the presence of halons makes the flames very sooty and luminous. This reduces the flame temperature by increasing the heat loss via radiation and contributes to the extinguishment process.

In the literature there is a controversy regarding the halon suppression mechanism: is it chemical or physical [see Ref. 28-30]? It is claimed that the superior suppression effectiveness of halons over other inerts such as CO_2 can be explained completely by accounting for their endothermic heat of decomposition, i.e. without considering the chemical mechanism of destruction of chain carriers. It is likely that both mechanisms are operative. The heat absorption due to endothermic heat of decomposition and heat loss due to radiation result in a lower flame temperature. The chain branching step is very sensitive to this temperature drop and the chain terminating steps become relatively more efficient at lower temperatures. Thus, there is a thermal reduction in the H atom concentration. Coupled with this thermal effect is the chemical removal of chain carriers. The fact that CF_3Br is more effective than HBr seems to support the dual mechanism hypothesis. However, others [68] believe that CF_3Br is more effective because of additional removal of H atoms due to the formation of HF . These issues need to be resolved via an integrated program with well-controlled experiments and supporting theoretical modeling like the one proposed here. The results will guide the development of new suppression agents. Also, such efforts must focus on diffusion rather than premixed flames. The proposed stagnation-point flow & counterflow diffusion flames are ideally suited for this purpose.

In summary, from the literature on various suppression agents (chemical or physical) it is

³Since, the molecular weight of halon 1301 is roughly 3.4 times that of CO_2 , on a mass basis it is about 1.6 times more effective for methane fires. It is also interesting to roughly compare the amount of water (if correctly applied) required to extinguish a given fire with the amount of halon 1301 needed for the same job. To maintain a fire with a heat release rate of 13.1KW, approximately 1 gm/sec supply rate of oxygen is needed. To extinguish the fire, 1.2 gms of CF_3Br is required/gm of O_2 . Now, assuming 10% heat feedback, water must be applied at 0.6 gms/sec to absorb 1.31KW. Thus, even if half the water is wasted it is as efficient as CF_3Br on a mass basis. Water, however, may cause permanent damage to some items.

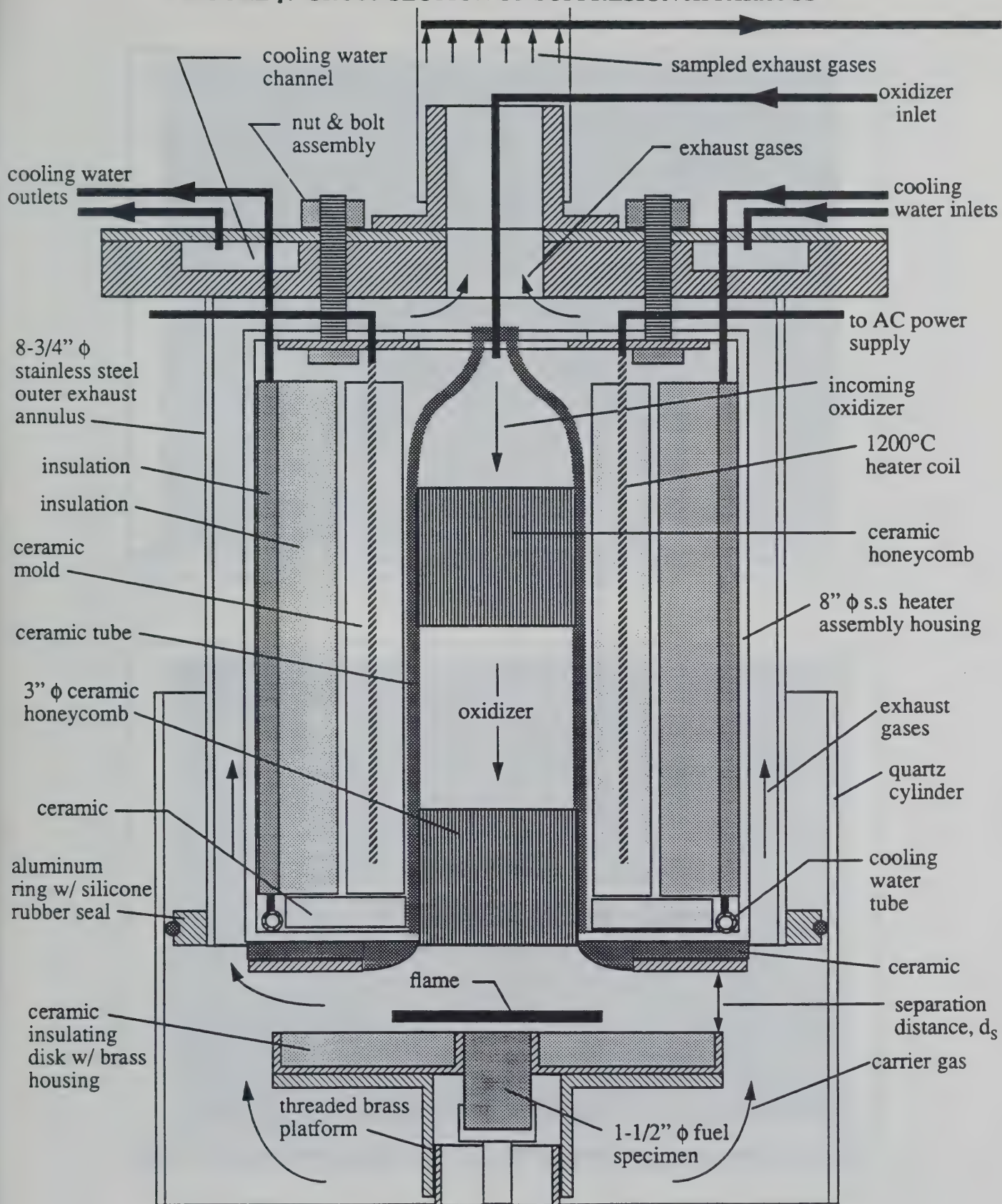
clear that there is little data on the amount of agent required and the rate of application needed to suppress fires and prevent their re-ignition (i.e. the suppression rate). As a result little comparison between various agents is possible. Also, qualitatively the suppression action of various agents is known (such as cooling of the condensed-phase, isolation of the fuel or oxidizer, etc.) but the quantitative details of the mechanisms responsible for the agent's action are not well known. This prevents development of new, perhaps more efficient, suppression agents. Even for water, there is little quantitative understanding regarding the extinguishment mechanisms (as will be clear from the later part of this proposal). Thus, it has not been possible to determine how much water is actually required and what should be the application strategy. The amount of water used is often about two orders of magnitude larger than that needed in controlled laboratory experiments [11, 12]. The current understanding of the suppression mechanisms of halons is also insufficient to provide a clear understanding of the important chemical mechanisms. Most importantly, there does not exist a scientific basis for comparing the suppression effectiveness of physical and chemical suppression agents.

3. SUPPRESSION EXPERIMENTS

To systematically address the above questions, suppression experiments are being conducted in well-controlled axis-symmetric stagnation-point flow and counterflow diffusion flames. These experiments provide a consistent experimental and theoretical basis for the evaluation of suppression effectiveness of different extinguishing agents and will help in clarifying their suppression mechanisms. For quantitative measurements, two unique experimental facilities have been constructed. These are: (i) *Stagnation-point flow apparatus*: which allows studying both the *gas-phase* and the *condensed-phase* suppression actions and enables transient chemical measurements in the exhaust gas. These measurements are being used to study the suppression mechanisms and quantify the suppression effectiveness. (ii) *Counterflow diffusion flame apparatus*: which allows detailed flame structure measurements but is limited to studying *gas-phase* suppression mechanisms (chemical and/or physical). Initially, the work is being done using the stagnation-point flow apparatus with water as the extinguishing agent and PMMA as the burning solid to establish a standard for comparison of suppression effectiveness of various agents.

The stagnation-point flow apparatus for suppression studies is schematically shown in Figure 1 and photographs of this apparatus with a flame on the PMMA sample during various stages of suppression by water are shown in Figures 2, 3, 4 and 5. This apparatus consists of a cylindrical 1200 °C furnace (approximately 20" tall) with a center ceramic tube for gas supply/exhaust. This ceramic tube supports a ceramic honeycomb heat exchanger and a ceramic honeycomb flow straightener. The entire furnace is supported by a specially designed ceramic flange which is supported by a water-cooled stainless-steel cylinder which hangs from a water-cooled circular aluminum plate. An outer concentric stainless-steel casing is used to direct the exhaust gases through the annular opening B. A 12" diameter quartz glass tube that can slide over the stainless-steel casing is used as an observation window. This glass tube sits on a soft silicone foam rubber support to prevent gas leakage. The cylindrical PMMA sample which is fed into the

FIGURE 1: CROSS-SECTION OF SUPPRESSION APPARATUS



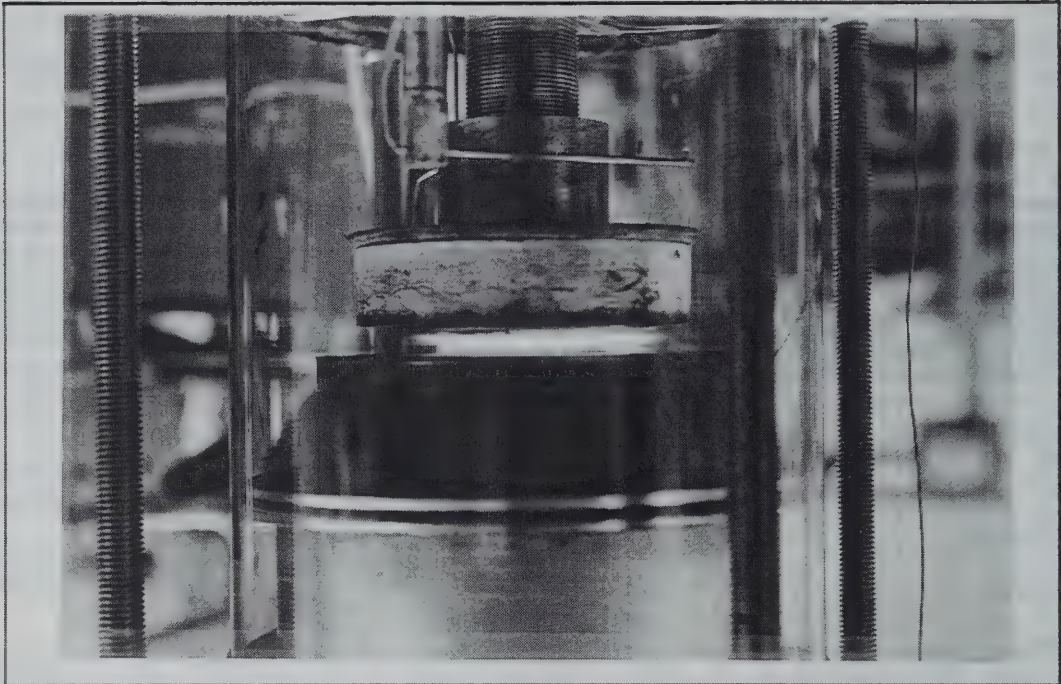


Fig. 2: A steady stagnation-point flow diffusion flame on the PMMA surface



Fig. 3: A Close-up of the flame on the PMMA surface showing soot streaks.

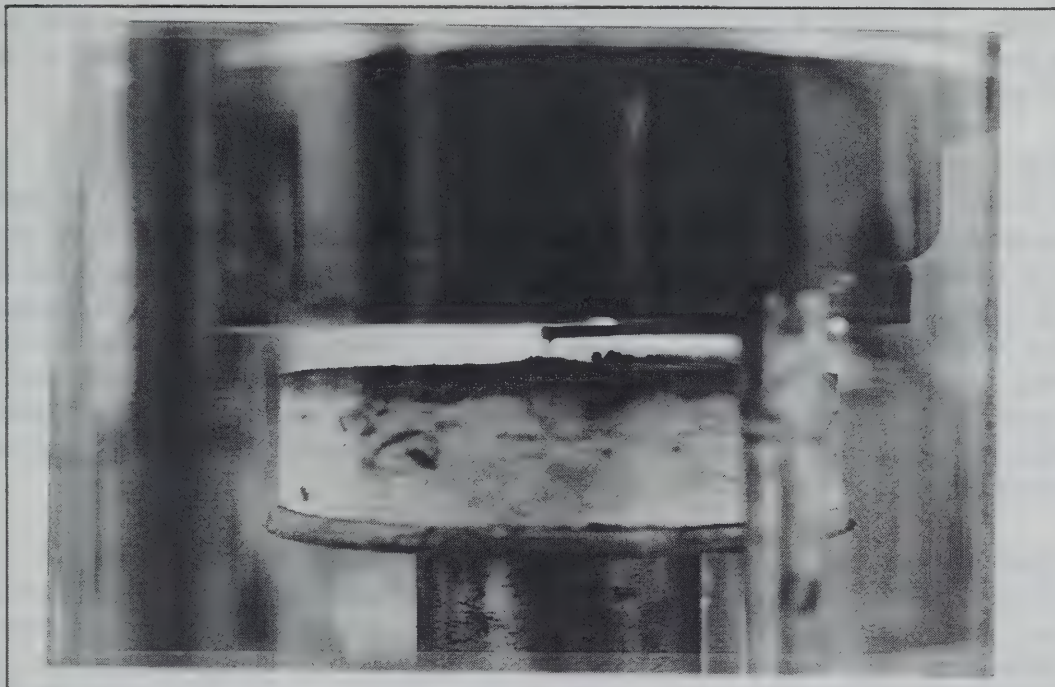


Fig. 4: Flame at the instant of water application. Note the water tube.

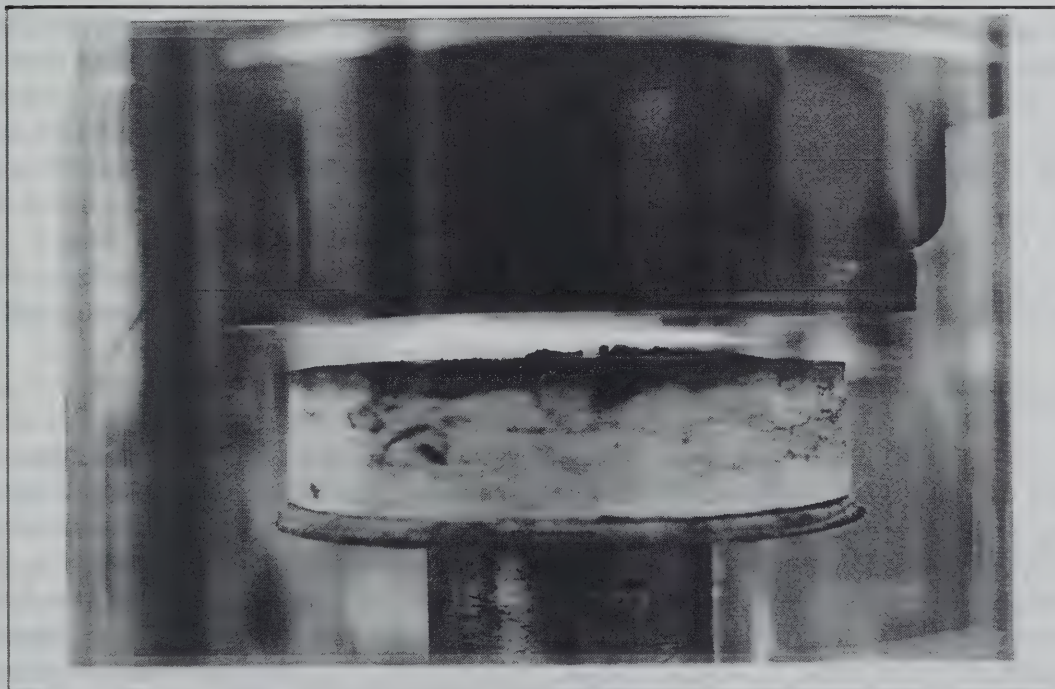


Fig. 5: Flame during water evaporation. Note the absence of soot streaks.

flame by a motor-driven mechanism is surrounded by ceramic insulation to ensure one-dimensional heat conduction. The entire bottom sample assembly is also supported by a water-cooled circular aluminum plate. A water-cooled droplet tube that can swing in and out of the hot burner zone is used to release water droplets on the sample surface (this tube can be seen in action in Fig. 4).

Prior to conducting the experiments, the water-cooled radiation shield protects the sample from the furnace radiation. The experiment begins when this radiation shield is removed. Measurements show that up to 4 W/cm^2 can be obtained on the sample surface in this configuration with a $\pm 5\%$ non-uniformity. The furnace heaters are electrically controlled and permit the control of external radiation on the sample surface. This apparatus also permits the control of composition, temperature, velocity and direction of gas flow. It permits transient measurements of exhaust gas composition, sample temperatures both with and without the application of the suppression agent. A video camera is used to continuously record the extinguishment history. A computer analysis of this record photographically measures the reduction in the flame size and intensity as well as the time to extinguishment.

Figure 2 shows a photograph of the apparatus with a steady flame on the PMMA surface. Figure 3 shows a close-up of a sooty flame supported by the PMMA sample as viewed through the quartz glass tube. The photograph is taken edgewise. The outer edges of the flame clearly show the soot streamlines. Fig. 4 shows the instant of water application on the PMMA sample. Figure 5 shows the stagnation-point diffusion flame after water application. Since the photograph is taken edgewise the hole in the flame created by water application is not visible. However, note that the soot emission from the flame edges has disappeared.

In addition to suppression by water application (representative results are described below), the stagnation-point flow and counterflow experiments are also being used to study and consistently quantify the suppression rate (defined by the attenuation in the energy release rate and measured by the exhaust gas composition) as a result of: (i) changes in the gas-phase composition due to addition of diluents (CO_2 , H_2O or N_2) or halons and their effect on the flame structure, and (ii) Increase in the strain rate. Later, heterogeneous surface reactions such as glowing char combustion will be studied in the same configuration. In fact, the earlier work of Evans [1] and Bhagat [2] was concerned with glowing char combustion. Temperature measurements across the diffusion flame in conjunction with an appropriate model will be used to determine the chemical heat release rate [41].

Experimental Results on Suppression by Water:

Qualitatively it is well known that when water is applied to the surface of a burning sample it quenches the production of fuel gases and produces water vapor instead. The effect of this action on the stagnation-point flow diffusion flame is to extinguish the flame in a circular region around the droplet. The size of the quenched flame region is a measure of the droplet influence area. Larger the droplet, larger is the influence area as shown in Figure 6. It is also clear from Figure 6 that the influence radius is much larger than the droplet radius and that the relationship is nonlinear [these measurements are taken from video photographs while viewing the flame at an angle]. Due to the extinguished zone inside the flame, the heat feedback from the flame to the solid reduces resulting in lower fuel production. For a given sample area and external radiation, the droplet size and application frequency that will lead to extinguishment may be experimentally determined.

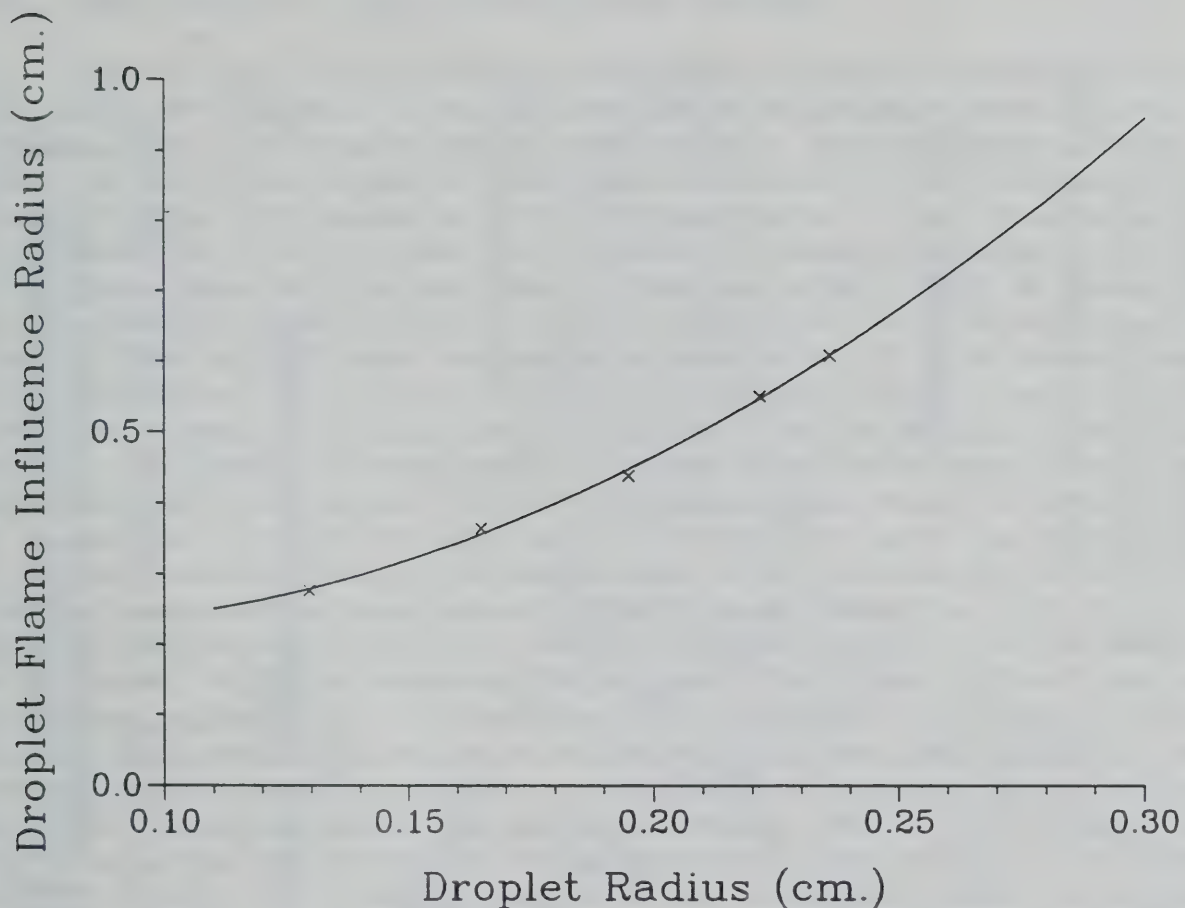


Fig. 6: Flame Influence Radius for Various Size Droplets from Stagnation-point Flow Experiments.

These experimental results can be used to obtain an engineering suppression diagram for a material. Such a diagram for PMMA is shown in Figure 7. Here, the non-dimensional droplet distribution is plotted against the non-dimensional external heat flux. Flaming combustion does not occur at heat fluxes below the minimum heat flux required for piloted ignition. This minimum heat flux for various moisture contents and environmental conditions was determined in our previous study on ignition. Under conditions of no water application, the entire zone beyond the minimum heat flux represents flaming combustion. If the droplet distribution is such that the entire sample surface is affected by water application (herein called the completely soaked condition), then the zone below the non-dimensional drop distribution of unity becomes non-combustible. When the sample is too large compared with the droplet affected zone and the external heat flux is larger than the minimum heat flux then burning conditions exist. Likewise, for a large non-dimensional external heat flux, burning conditions may exist even if the droplets are closely distributed on the sample. The boundary between the burning zone and the extinguished zone is termed as the *fire suppression boundary*. In Figure 7, for defining the non-dimensional droplet density, the droplet diameter was

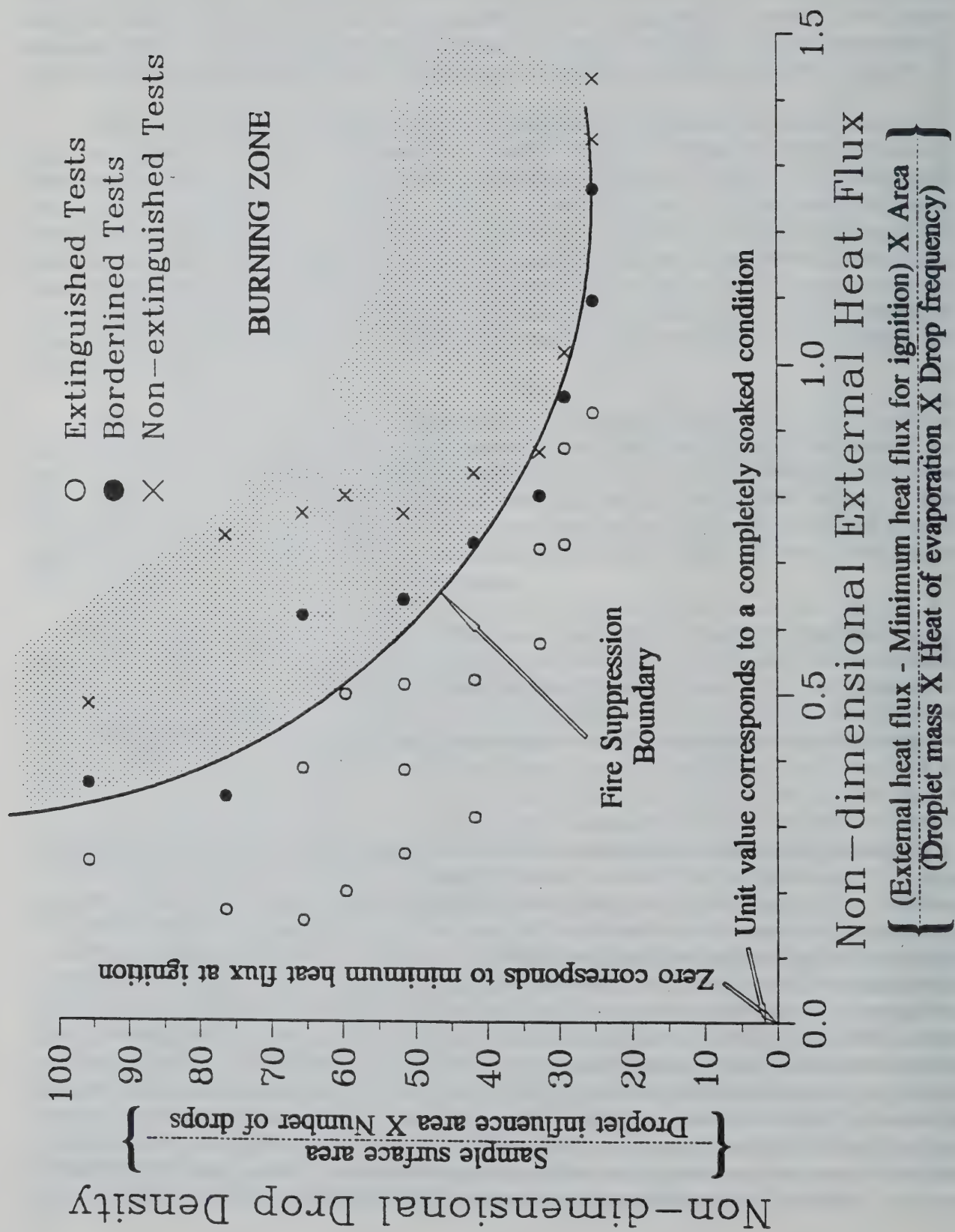


Fig.6: Fire suppression diagram for PMMA from the stagnation-point flow experiments

used to calculate the influence area. As can be seen from Figure 6, the actual influence area is much larger. However, this was not used in order to separate the effects.

Figures 8, 9 and 10 show the results of overall species composition measurements obtained in the exhaust port of Figure 1. These results correspond to the photographs shown in Figures 3, 4 & 5 and reveal a very interesting effect of water application. Such measurements are used to calculate the effect of water droplets (or other suppression agents) on the overall heat release rate. Figure 8 shows the CO_2 production rate and the O_2 consumption rate. Clearly, an increase in the CO_2 production rate and the O_2 depletion rate corresponds to an increase in the burning rate and vice versa. Figure 8 shows that when small amounts of water was applied ($< .2\text{ml}$), the burning rate was not significantly affected (or the small transient response could not be measured because a change in CO and total hydrocarbon concentrations was noted; see Fig. 9). As the amount of water applied was increased (see small arrows on the time-axis of Figures 8, 9 & 10), the burning rate first substantially increased and then decreased. For droplets $< .3\text{ml}$, the subsequent decrease was negligible. The increase in the burning rate was substantial and unexpected because it implies that instead of suppressing the flame we have enhanced it by applying water droplets. As shown in Fig. 10, this increase is consistent with a decrease in CO and total hydrocarbon concentrations. To explain this increase we first note that the flame (as shown in Fig. 3) was quite sooty and as evident from Fig. 9 it contained a substantial amount of CO and unburned hydrocarbons. Also, after water application, the flame became bluish (as can be seen from Figure 5) and did not have soot emission. We are currently working on understanding this phenomena. Our present hypothesis is that as a result of water evaporation CO , total hydrocarbons and soot are oxidized to CO_2 , depleting O_2 in the process. This hypothesis is supported by the fact that a non-sooty flame containing little CO , soot & unburned hydrocarbons does not show a similar increase in the burning rate due to water application. It seems that there are two simultaneous effects as a result of water application: (i) chemical enhancement of the burning rate (which is important only when the flames are sooty; Note: most fires are sooty), and (ii) physical cooling of the solid via water evaporation. The chemical effect has not been previously noted because water is usually applied in much greater quantities than needed and in this domain the physical cooling effect dominates. Thus, our understanding of suppression mechanisms even for the most common suppression agent needs further refinement.

4. THEORETICAL WORK

A transient theoretical (numerical) model for the stagnation-point-flow diffusion flame is being developed in conjunction with the above experiments. Significant effort has already been made toward this goal. The author started working on this model with the help of Dr. Howard Baum of NIST and will continue this collaboration. Also, existing numerical codes from SANDIA have been acquired to incorporate more realistic chemistry. This model will facilitate evaluation of the magnitudes of physical or chemical effects and also the changes in the flame structure caused by the suppression agent. In particular, it will allow calculations of the velocity field, changes in the energy release rate from the measured temperature profiles and changes in the production and destruction rates of various chemical species. Flame structure calculations & measurements will be very important for comparison between various suppression mechanisms and agents. The transient model will include simplified chemistry for soot formation in addition to the simplified suppression chemistry because several halogenated suppression agents are known to make the flame very sooty

CARBON DIOXIDE AND OXYGEN DEPLETION MEASUREMENTS DURING SUPPRESSION BY VARIOUS AMOUNTS OF WATER

Note: For small amounts of water the effect was not noticeable. As the quantity of H₂O increased, first the burning rate increased and then it decreased.

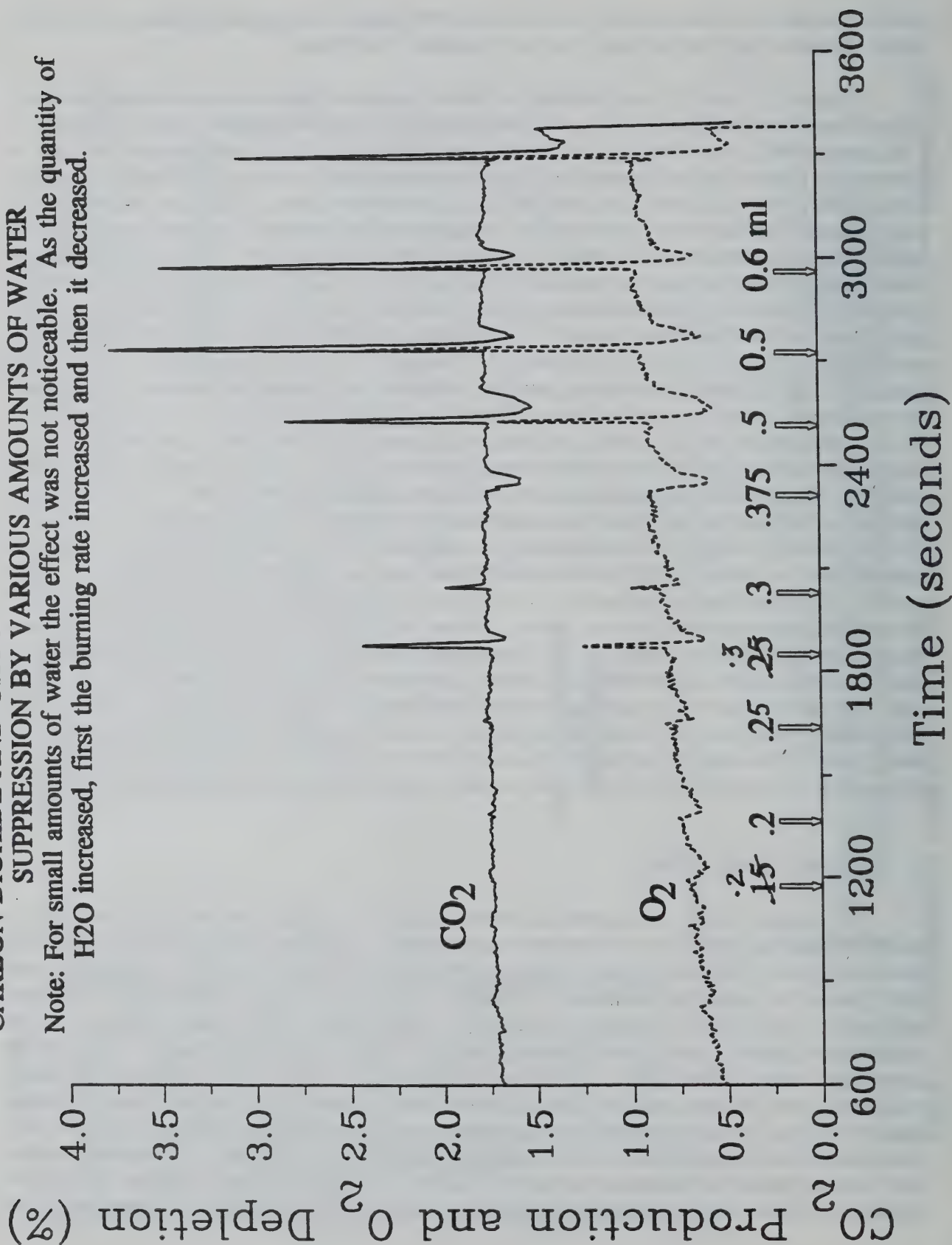


Figure 8

TOTAL HYDROCARBONS AND CARBON MONOXIDE MEASUREMENTS DURING SUPPRESSION BY VARIOUS AMOUNTS OF WATER

Note that both CO and HC decrease upon water application

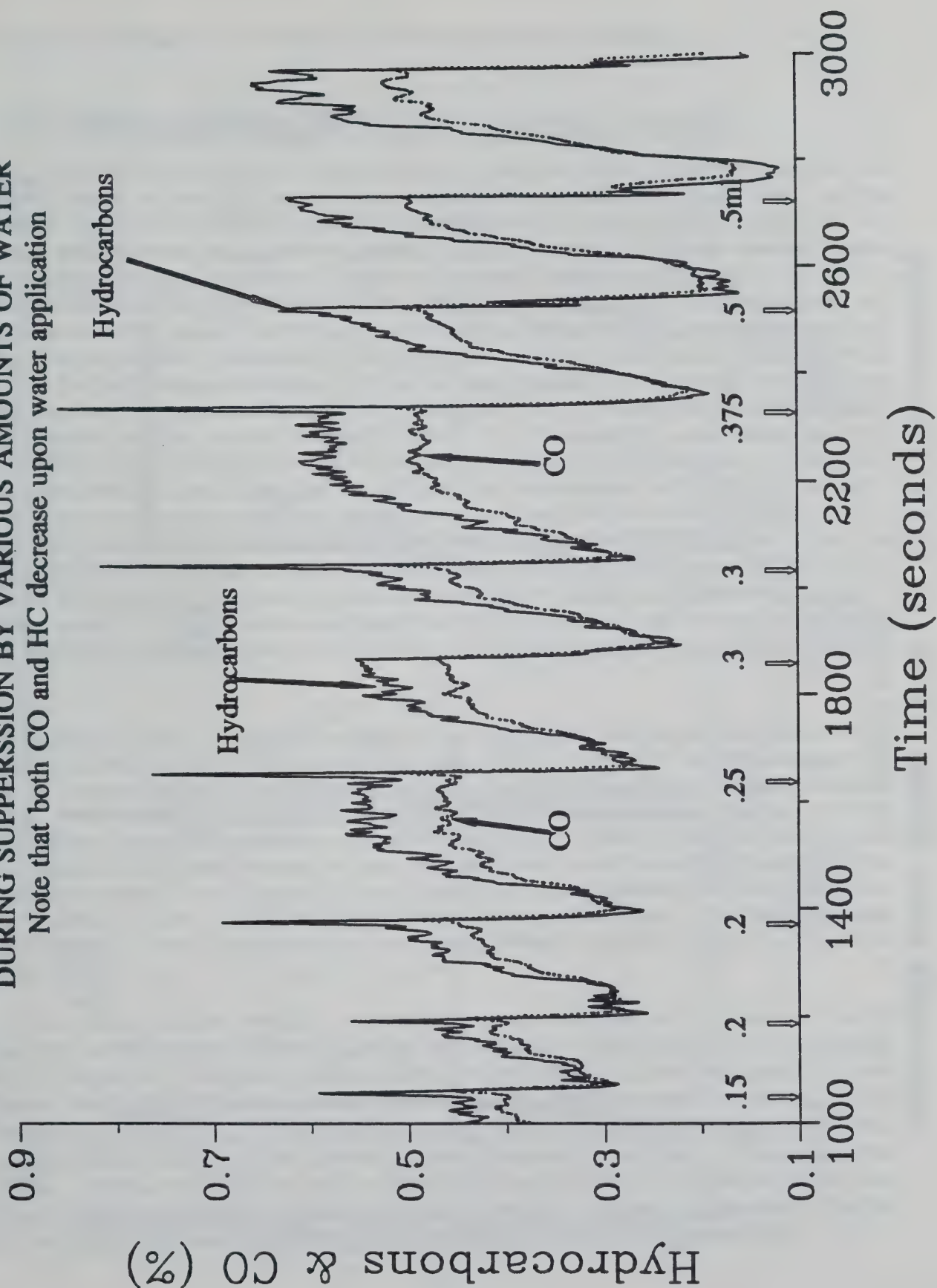


Figure 9

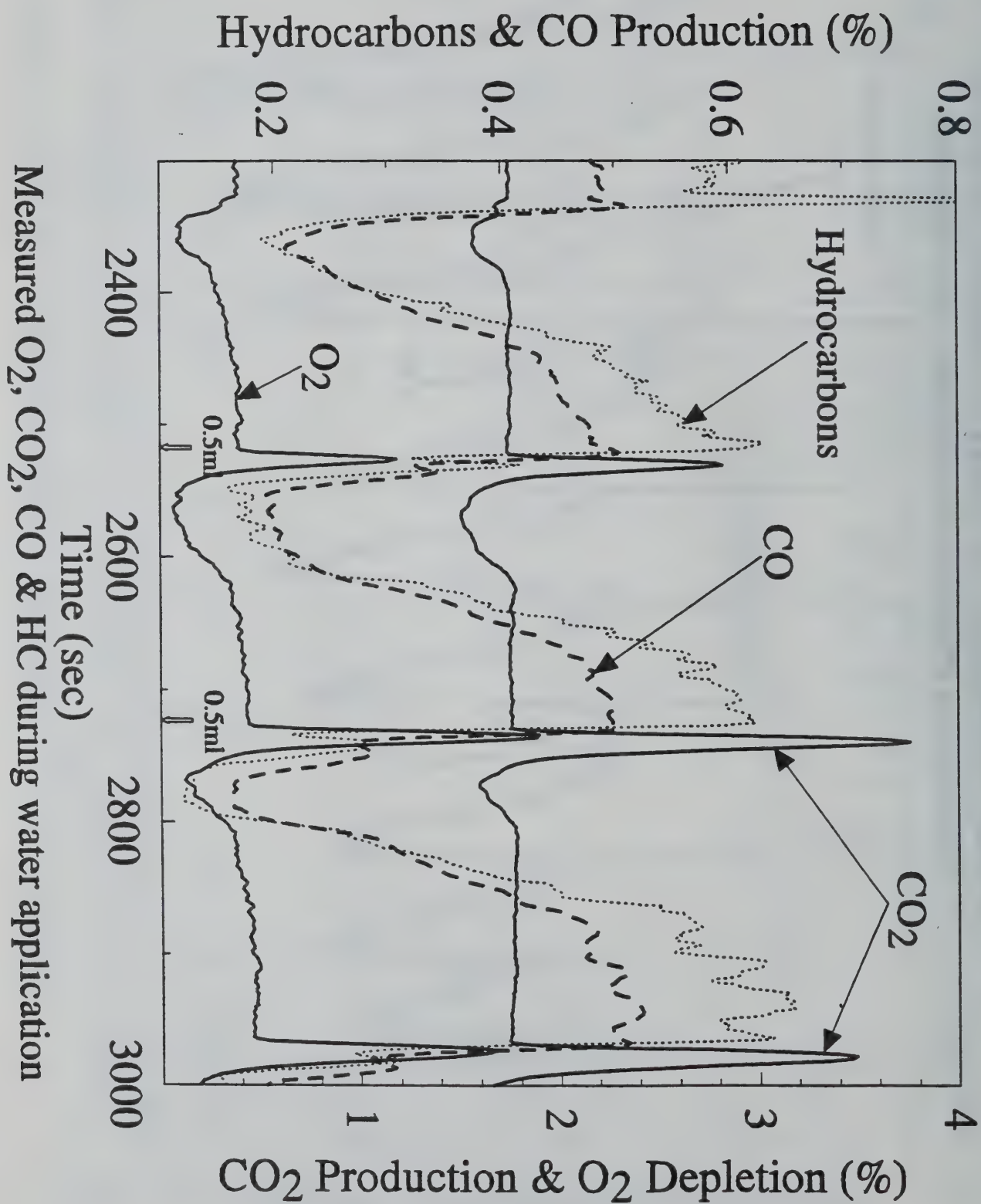


Figure 10

and luminous rendering flame radiation as an important heat loss mechanism⁴.

5. CONCLUSIONS & FUTURE WORK

In conclusion, our work thus far has raised more questions than it has provided answers. We believe that we do not even understand the mechanisms of fire suppression by water. Thus, we plan to continue the current investigation to identify the suppression mechanisms and quantify the fire suppression effectiveness for pure water droplets. This will provide a basis for comparison with other suppression agents (or actions). The results are being obtained as a function of: (i) air flow velocity or strain rate, (ii) O₂% in the air flow, (iii) external radiation. First some experiments are being conducted with gaseous fuels to enable understanding the gas-phase suppression mechanisms without the complications introduced by the solid-phase. Then, we will resume experiments with PMMA. For given external radiation, O₂% and air flow conditions, the transient overall energy release rate will be measured (by chemical gas analysis⁵) during water application on a steadily burning PMMA sample (as shown in Figures 8, 9 & 10). Temperature measurements across the flame will be used to calculate (with the help of theoretical models) the local energy release rates. These experiments will then be repeated with different size water droplets and application frequency. The difference in the energy release rate between the experiments with and without the water droplet provides a measure of the droplet effectiveness and quantifies the suppression rate. Work on studying the effect of additives to water and other suppression agents such as halons will be started. It will be interesting and important to consistently compare the suppression effectiveness of halons with pure water. For halons, some experiments will also be conducted in the counterflow diffusion flame apparatus to study its' effect on the flame structure and identify the suppression mechanisms.

⁴It seems that there is a contradiction between the postulated soot formation mechanism and the generally accepted halon suppression mechanism. As described in Section [3], suppression agents like CF₃Br act by reducing the H atom concentration and consequently slowing down the chain branching reaction. Where as, in the postulated soot formation mechanism, H atom concentration plays a critical role in forming important intermediates such as vinyl and ethynyl radicals for soot chemical growth. Thus, addition of CF₃Br should reduce the amount of soot formed in a diffusion flame because of lower H atom concentration that will result in reduced vinyl and ethynyl radical concentrations. Yet, when CF₃Br is added to a fuel, considerable increase in soot formation is observed. Clarification of these issues will yield a better understanding of both the suppression chemistry and the soot formation chemistry.

⁵For these transient chemical measurements, it is important to note that the time of occurrence of the event is different from the time the event is registered by the instruments. Also, the response of the system (gas flow lines plus analyzers) to a step input is usually quite different from a step function. Thus, appropriate time corrections must be made. These corrections can be divided into lag time (time taken by the instruments to reach the instruments) and response time (inability of the system to instantly respond to the change). The lag time and the system response to a step input will be experimentally measured and incorporated into a time correction scheme described in Appendix C of the Reference: A. Atreya, "Pyrolysis, Ignition and Fire Spread on Horizontal Surfaces of Wood," NBS-GCR-83-449, March 1984.

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This report presents a brief summary of previous research on fire suppression with the objective to provide guidance for the present work. Reasons for the adopted methodology are summarized and the apparatus developed for the study is described. Finally, some results for PMMA are presented along with conclusions and future work. Two experimental configurations are chosen for this study: (i) Stagnation-point flow apparatus: which allows studying both the gas-phase and the condensed-phase suppression actions and enables transient chemical measurements in the exhaust gas. These measurements are used to study the suppression mechanisms and quantify the suppression effectiveness. (ii) Counterflow diffusion flame apparatus: which allows detailed flame structure measurements but is limited to studying gas-phase suppression mechanisms (chemical and/or physical). Initially, the work is done using the stagnation-point flow apparatus with water as the extinguishing agent and PMMA as the burning solid to establish a standard for comparison of suppression effectiveness of various agents.

KEY WORDS (MAXIMUM 9 KEY WORDS; 28 CHARACTERS AND SPACES EACH; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES)

agents; diffusion flames; fire extinguishing; fire suppression; flame spread; infrared photography; polymethylmethacrylate; water

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